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Published in:
Proceedings of 2019 Fourteenth International Conference on Ecological Vehicles and Renewable Energies (EVER)

DOI (link to publication from Publisher):
10.1109/EVER.2019.8813645

Publication date:
2019

2019 Fourteenth International Conference on Ecological Vehicles and Renewable Energies (EVER)

Partial Charging Method for Lithium-Ion Battery State-of-Health Estimation

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***Abstract*—In this paper a lithium-ion battery State-of-Health (SoH) estimation method denoted Partial Charging Method (PCM) is proposed. The method is applied to Nickel-Manganese-Cobalt (NMC) battery cells exposed to cycling and calendar aging at 11 different test conditions. The influence of partial charging voltage intervals and charging rate on the SoH estimation error has been investigated. The results indicate that the PCM is independent on the charging rate and the aging conditions, and a SoH estimation Root-Mean-Square-Error of 2.4 % is achieved.**

***Keywords*—State-of-health estimation; Partial Charging Method; lithium-ion battery.**

I. INTRODUCTION

Knowing the actual capacity of a battery is important for mission critical applications. In an electrical vehicle (EV) for example, the actual battery capacity is related to the driving range of the vehicle. For practical reasons it is not always possible to measure the actual available capacity and it is therefore necessary to estimate it. Several methods for capacity or state-of-health (SoH) estimation methods has been presented in the literature [1], [2], [3], [4]. It is out of the scope of this paper to go through all of the methods, and this paper will therefore focus on a method based on Ah-counting. Different researchers have proposed to integrate the current in a specific interval for SoH estimation. In [5] the capacity of a lithium-ion polymer battery cell was estimated based on current integration between two State-of-Charge (SoC) values. An accuracy of 99.6 % was achieved. However this was only demonstrated for one particular SoH level. In [6], Nickel-Manganese-Cobalt (NMC) battery cells were exposed to cycling aging, and the capacity was estimated based on selected voltage intervals during discharge. An error of 3 % between the measured and estimated SoH was achieved. In [7], a method based on partial charging voltage profiles was propsed for capacity fade estimation of NMC battery cells exposed to calendar aging. A specific voltage inverval was selected for partial charging capacity determination. The average error was 2.5 %, but for SoH levels lower than 80 %, erros higher than 7 % was seen.

SoH estimation based on Ah-counting either during discharging or charging is a promising method. The purpose of the paper is therefore to further explore the method and propose a new method denoted Partial Charging Method (PCM). This paper is based on the same battery cells in [7], i.e. NMC cells. However, in this paper the cycling aging will also be considered in order to investigate the influence of the aging condition. The influence of the current level during charging is also considered. Finally, the voltage interval selection is investigated more systematic.

II. METHODOLOGY

If a SoH estimation method should be practical feasible, it is necessary that it does not require knowledge of the history of the battery. Therefore, the SoH estimation algorithm needs to be able to provide a satisfactory estimation error independent of the usage of the battery. Battery cells from the same EV battery module have therefore been exposed to both calendar and cycle aging.

A. Battery cells

The battery cells used in this work is based on 63.0 Ah NMC batteries. The battery cells are exposed to calendar and cycling aging conditions. Regularly during the aging tests, a full capacity measurement has been performed at the same temperature condition and C-rate for all cells. The specifications and conditions applied during the capacity measurement can be seen in Table 1.

TABLE 1: DATA OF BATTERY CELLS AND APPLIED CONDITIONS DURING CAPACITY MEASUREMENTS

Battery type	NMC
Nominal capacity, Q_{nom}	63 Ah
Maximum charging voltage	4.125 V
Minimum discharge voltage	3.000 V

Cut-off charging current	1.63 A (2.5 % of 1 C)
Discharge rate	1.0 C
Charge rate	0.2 C or 0.5 C
Temperature	25ºC

B. Aging conditions

The applied conditions during the calendar and cycling aging test can be seen in Table 2 and 3, respectively. The test matrices have been designed in such a way that the influence of individual stress factors are included.

TABLE 2: TEST MATRIX USED FOR CALENDAR AGING TEST

Temperature\SoC	10 %	50 %	90 %
7ºC		x	
35ºC		x	
40ºC		x	
45ºC	x	x	x

TABLE 3: TEST MATRIX USED FOR CYCLING AGING TEST. DISCHARGE RATE IS 1.5 C

Temperature\Charge rate	0.5 C	1.0 C	1.5 C
10ºC			X
25ºC			X
45ºC	X	X	X

In Fig. 1 it is seen how the voltage profile and therefore the discharge capacity Q_{dis} of a cell exposed to aging test change in compare to a fresh cell.

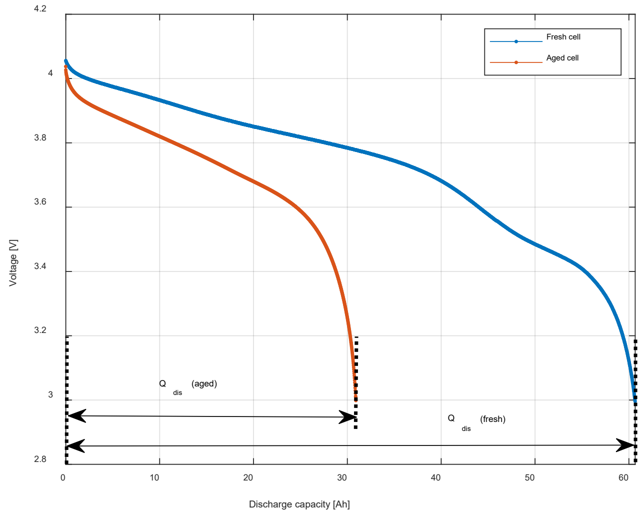


Fig. 1: Discharge voltage due to the discharge capacity of a fresh and aged battery cell. The full discharge capacity Q_{dis} due to the fresh and aged cell is also indicated. Condition: 1.0 C discharging.

C. Partial Charging Method

The PCM proposed in this paper is applied during charging as the name indicates. In most applications the purpose of the battery is to deliver energy during discharging. This means that the discharge current is mainly passively determined by the load. However, during charging the battery current is constant which means that the same conditions current wise can be applied each time.

A lower and upper voltage is being defined during the charging process. The partial charging capacity ΔQ_{cha} is then the capacity, which is being fed to the battery during the defined voltage interval. In Fig. 2 the charging capacity and charging voltage of a fresh cell and of an aged cell are presented. It is noticed that for the same voltage interval, the fresh cell has a higher partial charging capacity than the aged cell. Obviously, the full charge capacity Q_{cha} is also bigger for a fresh cell than for an aged cell.

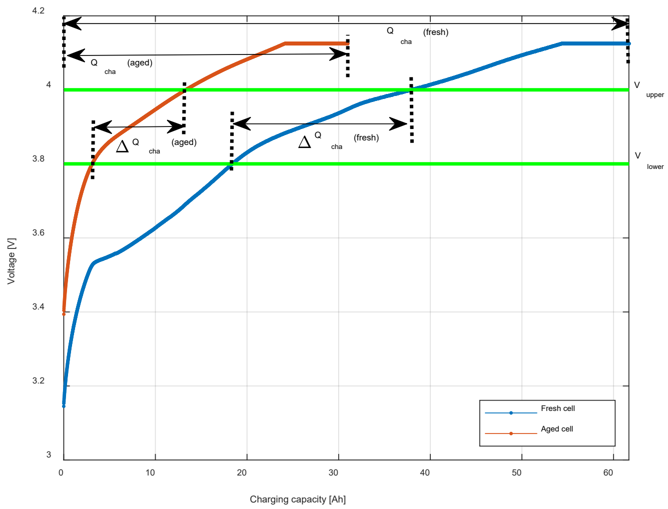


Fig. 2: Charging voltage due to the charging capacity of a fresh and aged battery cell. The partial charging capacity ΔQ_{cha} is defined by a lower V_{lower} and upper V_{upper} voltage. The full charging capacity Q_{cha} due to the fresh and aged cell is also indicated. Condition: 0.5 C charging.

The main hypothesis of the PCM is that a clear relationship between the partial charging capacity ΔQ_{cha} and the full charging capacity Q_{cha} can be established, and that there exist a clear relationship between the full charging capacity and full discharge capacity Q_{dis} also. Thereby, the full discharge capacity or SoH can be estimated only by determining the partial charging capacity defined by a lower and upper voltage level.

In this work the SoH is defined as the 1.0 C discharge capacity relative to the nominal discharge capacity, i.e.

$$SoH = 100 \cdot Q_{dis}/Q_{nom}. \quad (1)$$

III. RESULTS

A. Coulombic Efficiency

In order to apply SoH estimation during charging a clear relationship between the charge and discharge capacities is required. In Fig. 3 the full charge capacity and coulombic efficiency are shown versus the full discharge capacity for 0.5 C charging and 1.0 C discharging. The coulombic efficiency is defined as the discharge capacity over the charging capacity, i.e.

$$\eta = 100 \cdot Q_{\mathrm{dis}} / Q_{\mathrm{cha}}. \quad (2)$$

It is seen that the relationship between the discharge and charge capacity is linear for both aging conditions. The coulombic efficiency is however slightly lower for the cells exposed to calendar aging than the ones exposed to cycling aging. The average coulombic efficiencies for the two aging conditions are 99.0 % and 99.9 %, respectively, with an overall efficiency of 99.4 %. The coulombic efficiency has also been calculated for 0.2 C charging. The discharge rate is still the same, i.e. 1.0 C discharging. For this condition is the average efficiency 99.4 % for calendar aging, 99.7 % for cycling aging, and 99.5 % overall. Therefore, it is concluded, that for this study, the influence of the charge current rate is independent on the coulombic efficiency, when the discharge rate is 1.0 C. Secondly, it is concluded that for this study the aging method is negligible on the coulombic efficiency. It is therefore further on assumed that the discharging capacity can be obtained from the charging capacity, i.e.

$$Q_{\mathrm{dis}} \approx Q_{\mathrm{cha}}. \quad (3)$$

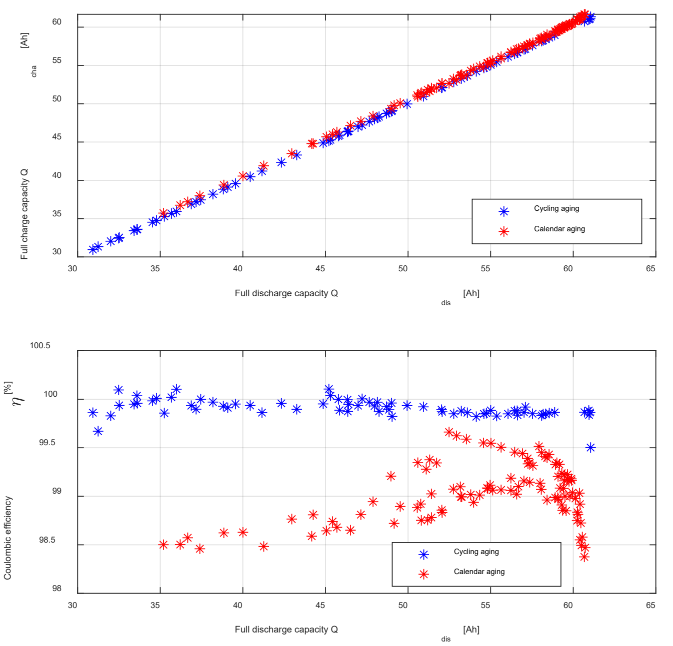


Fig. 3: Full charge capacity (top) and coulombic efficiency (bottom) versus full discharge capacity. Conditions: 0.5 C charging and 1.0 C discharging.

B. *Partial Charging Voltage Interval Investigation*

The voltage interval from 3.8 V to 4.0 V in Fig. 2 is only selected for illustration purpose. However, for all the cells, the partial charging capacity can be determined for the particular voltage interval. In Fig. 4, the full charging capacity as function of the partial charging capacity (obtained for the voltage interval 3.8 V to 4.0 V) is shown. The charging capacity can be estimated by the partial charging capacity using a first order polynomial, i.e.

$$Q^{*}_{\mathrm{cha}} = a \cdot \Delta Q_{\mathrm{cha}} + b, \quad (4)$$

where Q^{*}_{cha} is the estimated charging capacity, and a and b are polynomial coefficients. It is seen that for this particular voltage interval there is some deviation between the estimated and measured data.

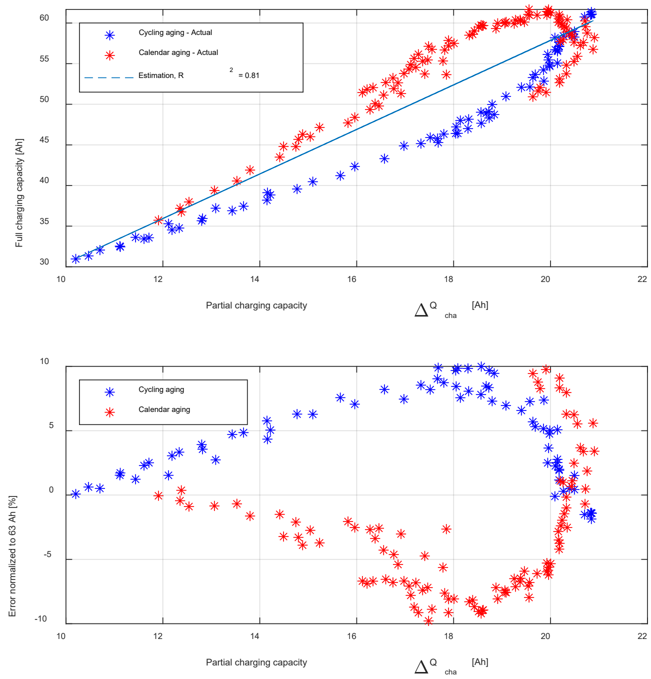


Fig. 4: Full charging capacity (top) and estimation error (bottom) versus partial charging capacity. Conditions: 0.5 C charging, V_{lower} = 3.8 V and V_{upper} = 4.0 V.

It was previously demonstrated that the coulombic efficiency practially is independent of the aging conditions and charging rate. The estimated discharge capacity Q^{*}_{dis}, state-of-health SoH^{*}, SoH estimation error are simply therefore

$$Q^{*}_{\mathrm{dis}} \approx Q^{*}_{\mathrm{cha}} = a \cdot \Delta Q_{\mathrm{cha}} + b \quad (5)$$

$$SoH^{*} = 100 \cdot Q^{*}_{\mathrm{dis}} / Q_{\mathrm{nom}} \quad (6)$$

$$Error = SoH^{*} - SoH. \quad (7)$$

In order to investigate the most suitable partial charging voltage interval is the Root-Mean-Squarre-

Error (RMSE) of the SoH estimation calculated for a wide range of the upper and lower voltage levels. It can be seen in Fig. 5 and Fig. 6 that the wider voltage interval is selected, the lower RMSE is obtained. This is not surprising as the partial charging capacity will approach the full charging capacity the bigger voltage interval. It should be mentioned, that the maximum upper voltage (4.15 V) of Fig. 5 and Fig. 6 actually is higher than the maximum allowed charging voltage of 4.125 V. This means that the constant voltage interval during the charging also is included in the partial charging capacity calculation. According to Fig. 5 and Fig. 6 this constant voltage interval has a positive effect on the SoH estimation RMSE. However, this constant voltage interval is a time consuming part of the total charging period.

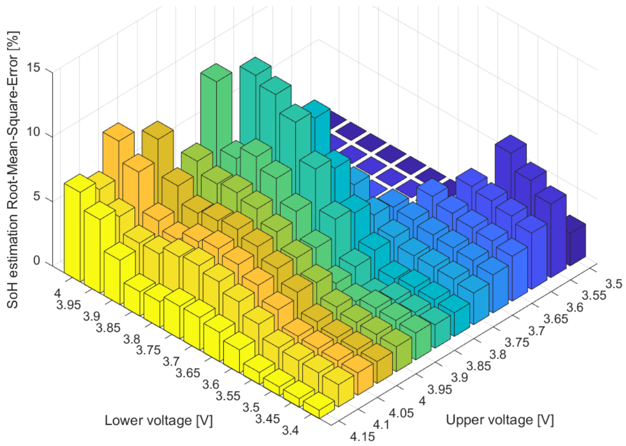


Fig. 5: SoH estimation RMSE for selected combinations of the upper and lower partial charging voltage levels. Conditions: 0.5 C charging and 1.0 C discharging.

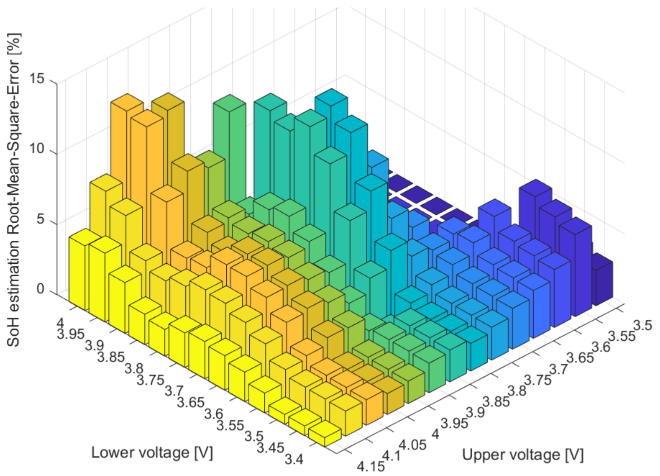


Fig. 6: SoH estimation RMSE for selected combinations of the upper and lower partial charging voltage levels. Conditions: 0.2 C charging and 1.0 C discharging.

The charging current rate does not have any significant influence on neither the SoH estimation RMSE values nor the pattern. For both the 0.2 C and 0.5 C charging is it noticed, that it's better (meaning lower RMSE) to have a low upper voltage than having a high lower voltage. As previously mentioned, the selection of the upper and lower partial charging voltage interval represents a trade off between accuracy and charging time. Very low lower voltage and very high upper voltage should therefore be avoided in order to have an acceptable charging time. Also, when looking at the charging voltage of an aged cell in Fig. 2 it is noticed that the minimum voltage is significantly higher than for a fresh cell due to the increase of the inner resistance of the battery. The lower voltage level should therefore not be selected too low, as it might not be possible to capture this level of a very aged battery cell.

Based on the derived considerations regarding partial charging voltage intervals, the following values are chosen: V_{lower} = 3.55 V and V_{upper} = 3.80 V for battery SOH estimation. In Fig. 7 the actual and estimated SoH and the corresponding SoH error can be seen for a 0.5 C charging rate. The SoH estimation RMSE is 1.8 % and thereby relatively low. A maximum error of almost 6 % is however also noticed for a SoH around 50 %. The estimated SoH is slightly higher than the actual SoH for the cells exposed to calendar aging, while for the cells exposed to cycling aging the estimated SoH is slightly lower than the actual SoH.

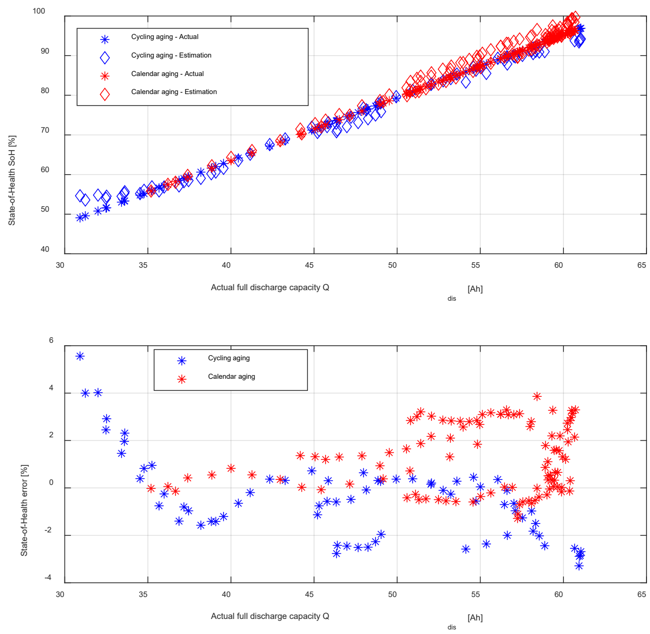
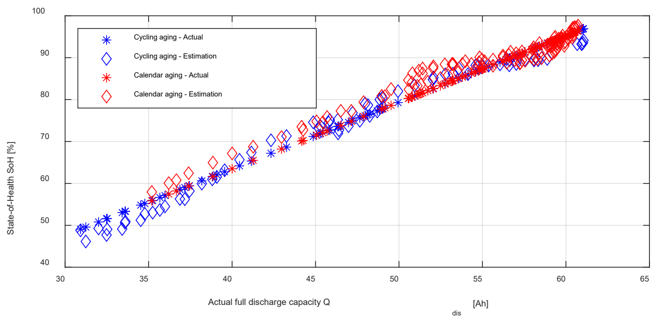


Fig. 7: Actual and estimated SoH (top) and SoH estimation error (bottom) versus actual full discharge capacity. Conditions: 0.5 C charging, 1.0 C discharging, V_{lower} = 3.55 V and V_{upper} = 3.80 V.

In Fig. 8 the actual and estimated SoH and SoH error can be seen for a 0.2 C charging. The maximum SoH error is still below 6 %, but the SoH estimation RMSE is 2.4 %, i.e. slightly higher than for 0.5 C charging. Intuitively the SoH error should be expected to be lower the lower charging rate is considered, as the influence of the voltage drop across the inner cell resistance thereby would be less significant. This is however not the case for this particular study, and the difference is therefore seen as an indication of the accuracy of the PCM rather than the influence of the charging rate. This means, that at least for charging rates of 0.5 C or lower, the accuracy of the PCM is independent on the current rate. Having more freedom in choosing the charging rate is an advantage of the PCM.



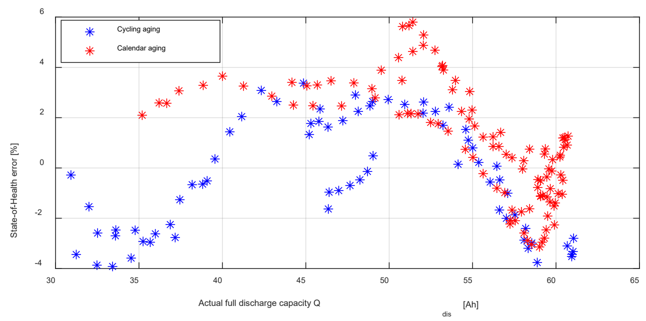


Fig. 8: Actual and estimated SoH (top) and SoH estimation error (bottom) versus actual full discharge capacity. Conditions: 0.2 C charging, 1.0 C discharging, V_{lower} = 3.55 V and V_{upper} = 3.80 V.

IV. Conclusion

In this paper a lithium-ion battery state-of-health estimation method denoted Partial Charging Method is proposed. The method estimates the discharge capacity by measuring a partial charging capacity defined by an upper and lower partial voltage level. The method has been applied on NMC battery cells exposed to both cycling and calendar aging tests performed at 11 different conditions. The coulombic efficiency was rounded to 100 % even though the cells exposed to calendar aging had a slightly lower average efficiency than the ones exposed to cycling aging (99.0 % vs. 99.9 % for 0.5 C charging and 99.7 % vs. 99.4 % for 0.2 C charging). The influence of the partial charging voltage interval has been investigated and an upper and lower voltage has been selected based on a compromise between accuracy and charging time. The charging rate did not indicate to have a significant influence on the SoH error, which is an advantage of the PCM. A SoH estimation Root-Mean-Square-Error of 1.5 % for 0.5 C charging and 2.4 % for 0.2 C charging was achieved. For both charging rates, the maximum SoH estimation error is below 6 %.

Acknowledgment

This work has been part of the Adaptive Battery Diagnostic Tools for Lifetime Assessment of EV batteries (BATNOSTIC) research and development project, project no. 64015-0611. The authors gratefully acknowledge EUDP Denmark for providing the financial support necessary for carrying out this work.

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